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Switching and Rectification of Phonon Polaritons of an Insulator at its Boundary with a Metal

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Abstract

The existence of surface polaritons in an insulator at its boundary with an ideal metal or a superconductor in a constant electric or magnetic field is predicted. The modes of these surface polaritons appreciably differ in opposite directions of the field, so that a change in the direction of the field signifies "switching on" or "switching off" of surface polaritons. In the presence of a magnetic field polaritons of a given frequency propagate only in one direction with respect to the magnetic field, which is the effect of rectification. The existence of a radiant surface polariton modes is predicted.

1. Introduction

It is well known that in massive insulator at its boundary with an ideal metal, surface polaritons do not exist [1]. We have shown that surface polaritons appear in the presence of a constant electric field directed along a normal to the contact plane [2] or in a magnetic field oriented in a contact plane [3]. Surface phonon polaritons appear due to a dynamic magnetoelectric (ME) interaction [4] and their penetration depth is inversely proportional to the value of the field. The modes of these polaritons belong to IR or optical regions of the spectrum and substantially depend on the directions of the fields and the propagation of the wave.

2. The Energy of Optical Phonons

For definiteness, we assume the insulator to be uniaxial (Z is the easy axis). The energy density W of optical phonons in external electric $\vec{E}$ and magnetic $\vec{H}$ fields can be written as

$$W=\frac{C_1}{2}P_z^2+\frac{C_2}{2}\left(P_x^2+P_y^2\right)+\frac{\Pi^2}{2\rho}-\vec{P}\vec{E}+\frac{1}{c\rho}\vec{P}\left[\vec{\Pi}\times\vec{H}\right] \tag{1}$$

Here $\vec{P}$ is the electric polarization, $\vec{\Pi}$ is the momentum density, $\vec{E}=\vec{E}_0+\vec{e}$, $\vec{H}=\vec{H}_0+\vec{h}$; $\vec{E}_0,\vec{H}_0$ are constant fields, $\vec{e}$ and $\vec{h}$ are alternating electric and magnetic fields; c is velocity of light; $\rho=m/V_0$, where m is the mass of a charge, V_0 is the elementary cell volume. Generally the electric polarization consists of ion and electron parts. In the IR region of the spectrum the contribution of ions to the

polarization is predominant, then m is the reduced mass of an ion-cation pair and $\vec{\Pi}$ is the elementary-cell moment. In the optical region of the spectrum the electron contribution to the polarization is much greater than the ionic one, then m is the electron mass and $\vec{\Pi}$ is the electron momentum. The last term in (1) corresponds to the dynamic ME energy [4]. This energy is a scalar so it is present in the energy of any crystal.

ME energy gives the contribution in an electric ($\vec{d}$) and magnetic ($\vec{b}$) inductions,

$$d_i = \varepsilon_{ik} e_k + 4\pi\chi_{ik}^{em} h_k,\ b_i = \mu_{ik} h_k + 4\pi\chi_{ik}^{em} e_k, \tag{2}$$

where ME susceptibility

$$\chi_{ik}^{em} = \frac{\partial P_i}{\partial h_k} = \left(\chi_{ki}^{me}\right)^* = \left(\frac{\partial m_k}{\partial e_i}\right)^* \tag{3}$$

3. Surface Phonon Polaritons in Electric Field

We consider a semi-infinite insulator ($z>0$) which is in contact with an ideal metal ($z<0$) in a constant electric field $\vec{E}_0$ directed along the Z axis. Polaritons propagate along the X axis. The solution of the Maxwell equations for an insulator with inductions (2) and $\mu_{ik} = \delta_{ik}$ in the absence of damping we take in the form

$$\vec{e}, \vec{h} \propto \exp\left[i(kx - \omega t) - k_0 z\right],\ k_0 \geq 0,\ z \geq 0 \tag{4}$$

where $k_0^{-1} = \delta_E$ is the depth of penetration of the field. At the boundary with an ideal metal $e_x = e_y = 0$ and without ME susceptibility surface polaritons do not exist because $d_x = 0$. In the presence of a constant electric field $\vec{E}_0$ directed along a normal to a contact plane the ME susceptibility χ_{ik}^{em} appears and takes the contribution in electric induction d_x,

$$\begin{gathered}\chi_{xy}^{em} = \frac{i\omega g P_0}{\omega^2 - \omega_0^2},\ P_0 = C_1^{-1} E_0,\ \delta_E = \frac{c\left(\omega^2 - \omega_0^2\right)}{4\pi\omega^2 g P_0} \\ \omega_0 = \bar{\omega}_0 \sqrt{C_2},\ g = e/mc,\ \bar{\omega}_0^2 = e^2/mV_0.\end{gathered} \tag{5}$$

Surface polaritons appear with the penetration depth δ_E which is inversely proportional to the value of electric field $\vec{E}_0$. For these polaritons only components of fields e_z and h_y are not zero. In our case $b_z = h_z = 0$, therefore all the results will be also hold true when an insulator is in a contact with a superconductor. The dispersion relation has the same form as for volume polaritons in the case of absence of electric field (Fig. 1)

$$k^2 = \frac{\omega^2}{c^2}\varepsilon_{zz}(\omega),\ \varepsilon_{zz} = \frac{\Omega_e^2 - \omega^2}{\omega_e^2 - \omega^2},\ \Omega_e^2 = \omega_e^2 + 4\pi\bar{\omega}_0^2,\ \omega_e = \bar{\omega}_0\sqrt{C_1} \tag{6}$$

The figure 1 corresponds to electron excitations (the optical region, $g<0$, m is the electron mass). The modes of surface polaritons are different for opposite orientations of the electric field. In a field directed into the insulator, the lower branch is excited, while in a field with opposite orientation

the upper branch is excited. The situation is reversed for ionic excitations ($g<0$). Thus surface polaritons with a fixed frequency can be "switched on and off" by changing the direction of the static electric field.

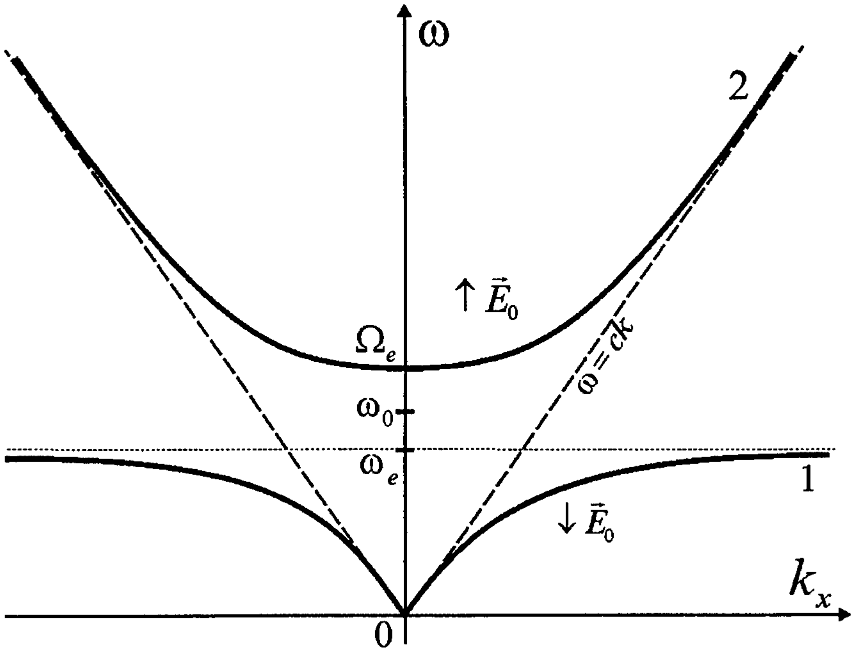

Figure 1

4. Surface Polaritons in Magnetic Field

In the presence of magnetic constant field $\vec{H}_0$, directed in the contact plane along Y axis the dynamic ME interaction induces the non-diagonal component of a dielectric tensor ε_{xz}.

$$\begin{gathered}\varepsilon_{xz} = -i\varepsilon' = -\frac{i8\pi\omega\omega_H\bar{\omega}_0^2}{\left(\omega^2-\omega_1^2\right)\left(\omega^2-\omega_2^2\right)},\ \omega_H = gH_{0y} \\ \omega_{1,2}^2 = \frac{1}{2}\left[\omega_0^2+\omega_e^2+2\omega_H^2 \mp \sqrt{\left(\omega_0^2-\omega_e^2\right)^2+8\omega_H^2\left(\omega_0^2+\omega_e^2\right)}\right]\end{gathered} \tag{7}$$

The penetration depth of polaritons δ_H is inversely proportional to the value of magnetic H_{0y}. The dispersion relation and the depth of penetration are following:

$$k_x^2 = \frac{\omega^2}{c^2}\frac{\left(\omega^2-\Omega_1^2\right)\left(\omega^2-\Omega_2^2\right)}{\left(\omega^2-\omega_1^2\right)\left(\omega^2-\omega_2^2\right)},\ \delta_H = \frac{c^2k_x}{\omega^2\varepsilon'(\omega)} > 0 \tag{8}$$

where the expressions for $\Omega_{1,2}$ we obtain from (7) by the replacement ω_e on Ω_e. Surface polariton modes in magnetic field are shown in Fig. 2.

In optical region ($g<0$) for $H_{0y}>0$ the polariton modes are thick solid curves. The modes are not close to each other and the spectrum is strongly nonreciprocal: there are two modes for polaritons

running to the left and one mode for polaritons running to the right. Surface polaritons with a given frequency propagate only in one direction with respect to magnetic field. This is the effect of the rectification. The substitution of $-k_x$ for k_x in Fig. 2 corresponds to the inversion of the magnetic field $H_{0y} \to -H_{0y}$. In this case, the dashed curves are the modes of surface polaritons.

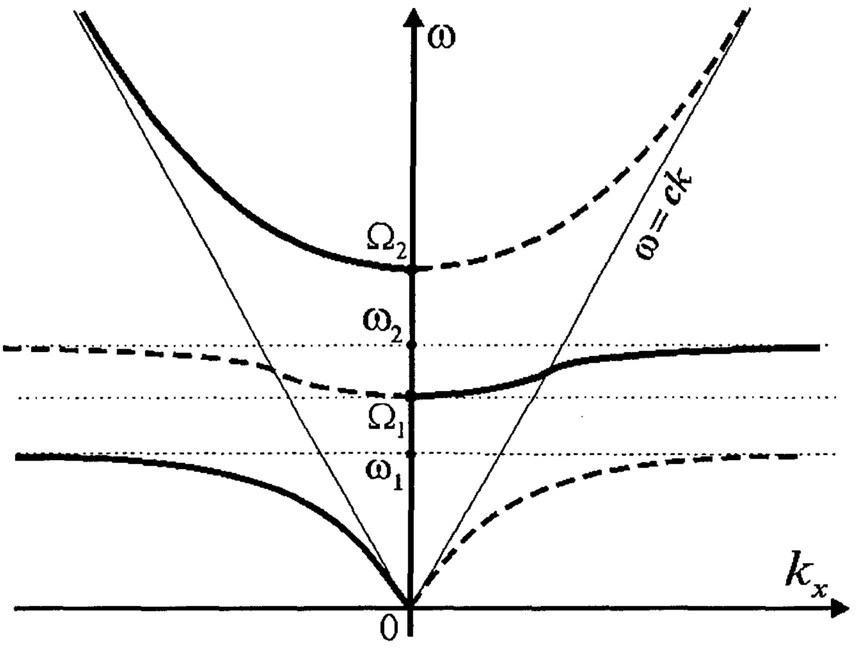

Figure 2

5. Conclusions

Thus, in the presence of a constant electric or magnetic fields the surface polaritons exist in a semi-infinite insulator, which is in contact with an ideal metal or a superconductor. The depth of penetration of polariton field into the insulator is inversely proportional to the value of the field and it is less in optical region than the one for IR region. So, in the optical region of the spectrum $\delta_H \propto c/gH_0$. If $H_0 = 10\,\text{T}$, $\delta = 10^{-2}\,\text{cm}$.

The frequency regions in which surface polaritons exist depend strongly on the direction of the field so a change of the sign of the field signifies the "switching off" or "switching on" of polaritons with a given frequency. In the presence of magnetic field the spectrum is a strong nonreciprocal: surface polaritons propagate only in one direction with respect to magnetic field (the effect of rectification).

The upper modes are radiant modes and may be excited by a direct interaction with electromagnetic wave.

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